Test synopsis of:

Proton Response of 4^{th}-Generation 350 GHz UHV/CVD SiGe HBTs

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Abstract—**We report, for the first time, the impact of proton irradiation on 4^{th}-generation SiGe HBTs having an record peak cutoff frequency of 350 GHz. The implications of aggressive vertical scaling on proton tolerance in SiGe HBTs is investigated using transistors of varying breakdown voltage, and through comparisons of *ac* and *dc* figures-of-merit to results from prior SiGe technology nodes. We demonstrate that SiGe technology continues to exhibit impressive total dose tolerance, even at unprecedented levels of vertical profile scaling and frequency response.**

I. Introduction

Silicon-Germanium Heterjunction Bipolar Transistors (SiGe HBTs) are emerging as a technology of choice for terrestrial monolithic RF, microwave, and millimeter ICs used in broadband communications systems. SiGe HBTs exhibit performance characteristics as good or better than those of III-V technologies, while leveraging seamless integration with low cost, high yield Si CMOS manufacturing [1]. This synergy enables the technology to be incorporated into SiGe HBT BiCMOS system-on-a-chip (SoC) integration schemes that can be tailored to produce "commercial-off-the-shelf" (COTS) modules for communications systems. Previous investigations have demonstrated that such commercial SiGe HBTs are inherently tolerant to high (Mrad) levels of ionizing radiation [2]. These attractive attributes potentially enable SiGe technology to be a formidable contender for niche space-borne applications.

The 4^{th}-generation SiGe HBTs under investigation were fabricated at IBM Microelectronics (IBM 9T), and achieve a remarkable peak cutoff frequency (f_T) of 350 GHz, a record for any Si-based transistor. This unprecedented level of frequency response represents a 67% increase over the previous SiGe HBT performance record, and was fabricated in 120 nm 100% Si-compatible technology. The associated BV_{CEO} and BV_{CBO} are 1.4 V and 5.0 V, respectively, yielding an $f_T BV_{CEO}$ product well above the so-called 200 GHzV "Johnson limit" [3]. A discussion of the scaling methodologies employed in the first two distinct technology generations (IBM 5HP and 7HP), and the resultant effects on proton tolerance, was presented in [4], and for brevity is not revisited here. In the 3^{rd}-generation SiGe technology (IBM 8HP), an improvement in f_T to 200 GHz was realized only through fundamental changes in the physical structure of the transistor. Specifically, a reduced thermal cycle "raised extrinsic base" structure was implemented using conventional deep and shallow trench isolation (STI), and an $in-situ$ doped polysilicon emitter. The SiGe base region featured an unconditionally stable, 25% peak Ge, C-doped profile deposited using UHV/CVD epitaxial growth techniques [5]. In the case of the present IBM 9T technology, performance enhancements were realized solely through careful profile optimization and aggressive vertical scaling of the base and collector regions, resulting in a record emitter-to-collector transit time (τ_{EC}) of 0.45 psec[6]. A representative device cross-section is depicted in Figure 1. The impact of combining this

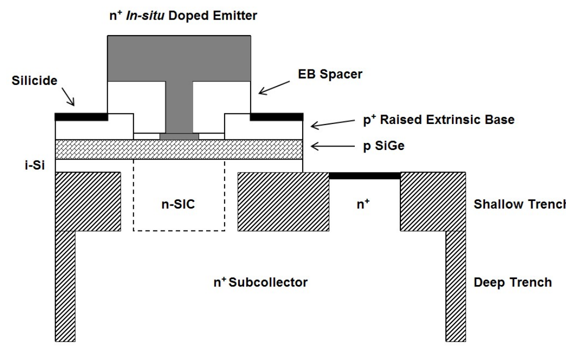

Fig. 1. Representative cross-section of a 4^{th}-generation SiGe HBT.

unprecedented level of vertical profile scaling on the proton radiation response is investigated for the first time using these 350 GHz SiGe HBTs. A comprehensive picture of the variation in total dose tolerance across multiple SiGe technology platforms is presented by drawing quantitative comparisons between 1^{st} (IBM 5HP), 2^{nd} (IBM 7HP), 3^{rd} (IBM 8T), and now 4^{th} (IBM 9T) generation SiGe technology nodes.

II. Experiment

These 4^{th}-generation 350 GHz SiGe HBTs investigated here had an emitter area (A_E) of $0.12 \times 2.5 \mu m^2$, and were compared with 0.50 μm 50 GHz (IBM 5HP), 0.20 μm 120 GHz (IBM 7HP), and 0.12 μm 200 GHz (IBM 8T) technology nodes measured under identical conditions in order to facilitate unambiguous comparisons. Multiple breakdown voltage transistors were fabricated on-wafer using different collector implantation, and were used to assess the impact on proton displacement effects in the collector doping profile.

The samples were irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radia-

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tion source (Ta scattering foils) located several meters upstream of the target establish a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 20 nA to 100 nA allow testing with proton fluxes from 1×10^9 to 1×10^{12} proton/cm^{2}sec. The dosimetry system has been previously described[7] [8], and is accurate to about 10%. At proton fluences of 1×10^{12} p/cm^2 and 5×10^{13} p/cm^2, the measured equivalent total ionizing dose was approximately 135 and 6,759 krad(Si), respectively. The SiGe HBTs were irradiated with all terminals grounded for the *dc* measurements and with all terminals floating for the *ac* measurements at proton fluences ranging from 1.0×10^{12} p/cm^2 to 5.0×10^{13} p/cm^2. The *ac* measurement samples, which were irradiated at 7.0×10^{12} p/cm^2 and 5.0×10^{13} p/cm^2, were measured and then subsequently re-irradiated at the same fluence levels. Thus, when re-characterized, the *ac* samples were irradiated to maximum net proton fluences of 1.4×10^{13} p/cm^2 and 1.0×10^{14} p/cm^2. We have previously shown that SiGe HBTs are not sensitive to applied bias during irradiation [1]. Wirebonding of *ac* test structures is not compatible with robust broadband measurements, and hence on-wafer probing of S-parameters (with terminals floating) was used to characterize the high-frequency device performance. The samples were measured at room temperature with an Agilent 4155 Semiconductor Parameter Analyzer (*dc*) and an Agilent 8510C Vector Network Analyzer (*ac*) using the deembedding techniques discussed in [9].

III. *dc* RESULTS

The post-irradiation forward-mode Gummel characteristics on a low-breakdown voltage (1.4 V BV_{CEO}) transistor is shown in Figure 2 and clearly indicates a base current (I_B) that monotonically increases with proton fluence. This classical signature

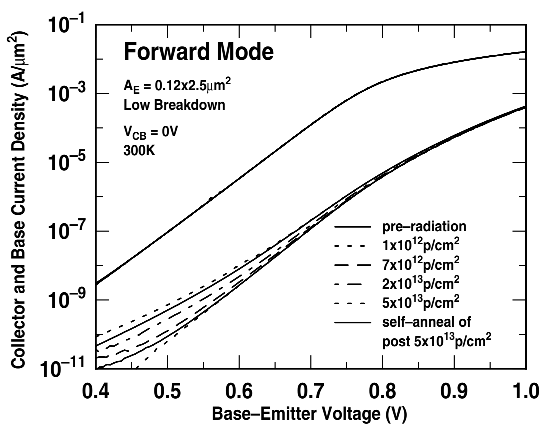

Fig. 2. Forward-mode Gummel characteristics of the 350 GHz SiGe HBT during radiation exposure.

of radiation-induced damage in SiGe HBTs [10], is attributed to proton-induced generation/recombination (G/R) trap centers, and are physically located at the emitter-base spacer oxide and shallow-trench isolation (STI) edges. The irradiated devices were subsequently allowed to "cool-down" and then were re-measured approximately 6 weeks after the 5×10^{13} p/cm^2 exposure. This resulted in a slight decrease in I_B, indicative of spontaneous "self annealing" of the radiation-induced G/R traps. Similar results were obtained for the inverse-mode Gummel characteristics (emitter and collector terminal swapped). Interestingly, at a fluence of 1×10^{12} p/cm^2, there is a slight reduction in I_B at very low current levels from pre-radiation values, and is attributed to an underlying radiation-induced annealing mechanism. The resultant forward-mode *dc* current gain, (β), is shown in Figure 3, and shows a consistent degradation for increasing proton fluence, as expected. Three metrics were used

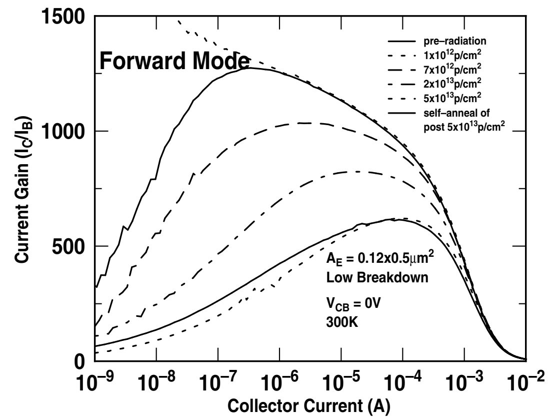

Fig. 3. Forward-mode current gain of the 350 GHz SiGe HBT during radiation exposure.

to compare the proton tolerance across multiple SiGe technology generations: the peak β degradation, and the forward-mode and inverse-mode I_B degradation (sampled at V_{BE}=0.6V). The results are shown in Figures 4, 5, and 6.

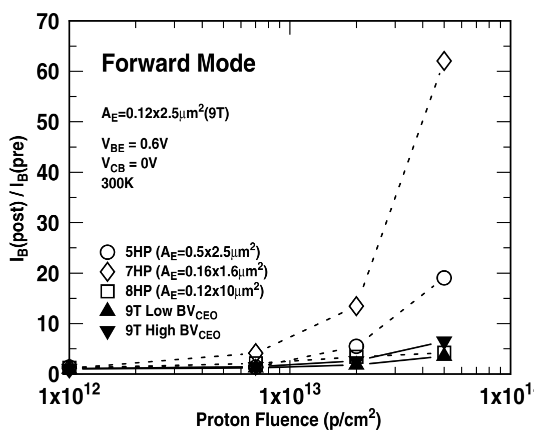

Fig. 4. Forward I_B degradation for 5HP, 7HP, 8T, and 9T SiGe technology nodes.

Our previous work attributed the increased radiation-induced I_B leakage in 2^{nd}-generation (IBM 7HP) SiGe HBTs over that found in 1^{st}-generation SiGe HBTs to the increased electric field in the emitter-base junction at the device periphery, and associated with the higher local doping associated with vertical and lateral scaling. [4]. The substantial improvement in both the 3^{rd} (8T), and the 4^{th} (9T) post-radiation I_B response (in both forward and inverse mode) with fluence is quite surprising given the strongly reduced thermal cycles and hence presumably less-robust oxide-to-Si interfaces present. For the inverse mode characteristics, which are dominated by radiation damage in the collector-base junction, we attribute the dramatically improved

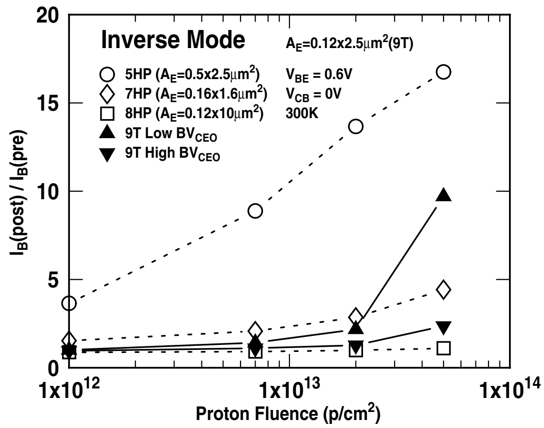

Fig. 5. Inverse I_B degradation for 5HP, 7HP, 8T, and 9T SiGe technology nodes.

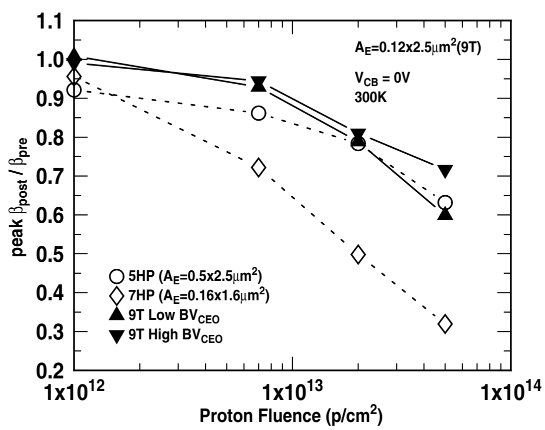

Fig. 6. β degradation for 5HP, 7HP, 8T, and 9T SiGe technology nodes.

radiation response over earlier technology generations to the elevation of the extrinsic collector-base junction to a physical location above the shallow-trench edge. This is inherently achieved in migrating to the new raised extrinsic base structure. The results reported here on the 3^{rd}-generation (8T) results are only newly fabricated, more ideal transistors, yet remain consistent with that reported on pre-production, non-ideal 3^{rd}-generation devices [2]. In additional, the improvement in proton-induced I_B degradation obtained using a different physical structure in 8HP, has been preserved in the vertically scaled 9T device, alluding to continued EB spacer optimization with scaling.

Interestingly, the inverse-mode I_B degradation comparison for 9T shown in Figure 5 indicates that the low breakdown (350 GHz) devices are more susceptible to proton induced damage at the CB junction than for higher breakdown transistors fabricated with lower collector doping. Presumably, the increased collector doping (N_C) used to suppress barrier effects and realize peak f_T at higher J_C leads to a collector-base junction which is physically closer to the G/R traps generated at the STI edge. Thus, for the same STI proton-induced trap density, one would expect more net recombination in the CB junction of the lower breakdown transistor. This is consistent with data in both in Figure 5 and Figure 8 as discussed further below.

IV. Breakdown Considerations

The extrinsic transcounductance (g_m) of both devices, shown in Figure 7, clearly depicts the onset of the high injection heterojunction barrier effect (HBE) for the high breakdown device at a much lower I_C than that of the low breakdown device (consistent with the observed higher BV_{CEO} and lower f_T). Additionally, there is minimal shift in the onset of HBE with increasing proton fluence, suggesting that an observable amount of displacement-damage-induced dopant de-ionization occurs in the higher breakdown transistor. Measurements to assess the impact of irradia-

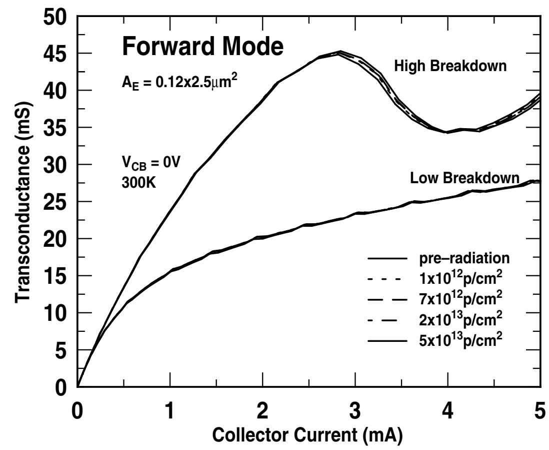

Fig. 7. g_m vs. I_C for the high and low breakdown transistors.

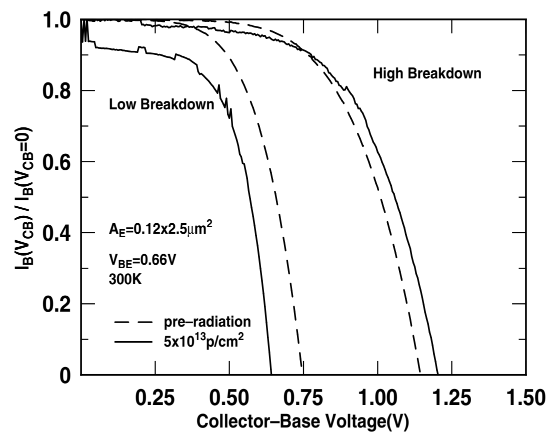

Fig. 8. Normalized base current as a function of bias voltage for the high and low breakdown transistors.

tion on neutral base recombination (NBR) and radiation-induced hole lifetime changes are shown in Figure 8, and illustrate some interesting differences in the radiation response of the two different breakdown transistors. The low breakdown device, with its increased N_C, exhibits a much stronger post-radiation NBR component at low V_{CB}, indicative of the formation of radiation-induced traps in the base. In addition, note that the post-radiation breakdown voltage itself (evidence by the voltage at which I_B = 0) increases for the high breakdown device, while it decreases for the low breakdown transistor. This is consistent with the differences in the current gain degradation between the two device types (Figure 6).

V. *ac* RESULTS

The transistor scattering parameters (S-parameters) were characterized to 45 GHz over a range of bias currents, each at constant V_{CB}. The data was subsequently de-embedded using standard "open-short" structures to calculate the small-signal current gain (h_{21}) and the Mason's unilateral gain (U). Values for f_T were obtained using a -20dB/decade slope extrapolation of h_{21} for different proton fluences, as shown in Figure 9 for both pre-radiation and a post-radiation fluence of 5×10^{13} p/cm^2. An overlay of pre- and post-radiation measurements of f_T vs J_C for 5HP, 7HP, 8T, and 9T verify that the *ac* performance of SiGe

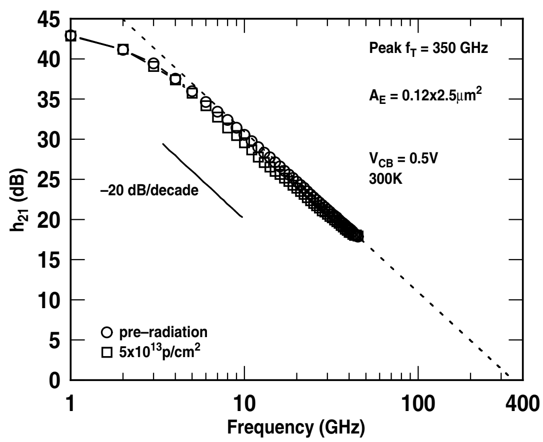

Fig. 9. An h_{21} extrapolation for a 350GHz f_T.

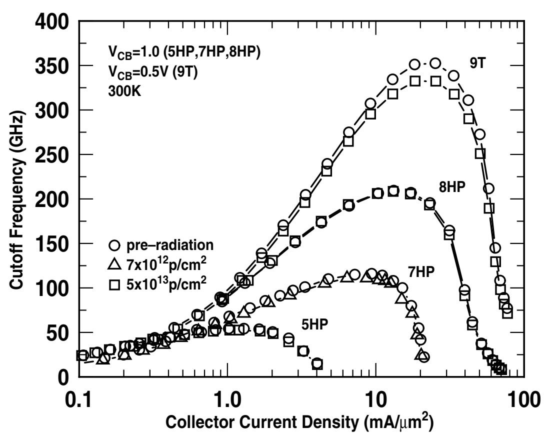

Fig. 10. Pre- and post-radiation f_T for 5HP, 7HP, 8T, and 9T SiGe technology nodes.

HBTs continue to be remarkably resistant to damage by ionizing radiation, even for novel device structures employing both aggressive vertical scaling and reduced thermal cycle processing. This is clearly excellent news. The dynamic base resistance (r_{bb}), extracted from measured S-parameters and shown in Figure 11, shows a slight increase at 5×10^{13} p/cm^2, for J_C close to peak f_T. This is consistent with an observed f_{max} degradation in the device, previously attributed to displacement effects in the neutral base region and the deactivation of boron dopants [2]. The forward transit time (τ_{EC}), as a function of proton fluence, for 7HP, 8T, and 9T SiGe HBTs are given in Figure 12. Additional vertical scaling enables further reduction in τ_{EC} to a record value

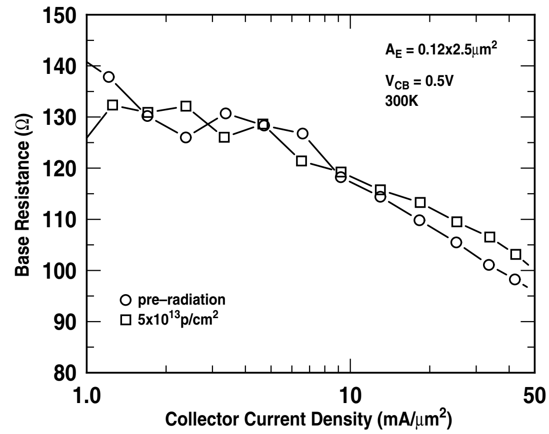

Fig. 11. Pre- and post-radiation r_{bb} variation with J_C.

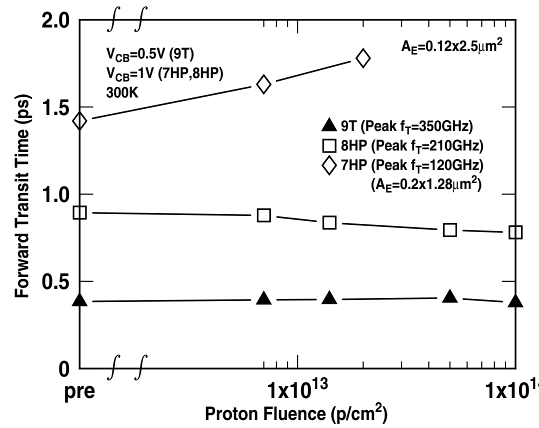

Fig. 12. The τ_{EC} variation with fluence for 7HP, 8T, and 9T SiGe HBTs.

of 0.45 psec, and unlike for 1^{st} and 2^{nd}-generation SiGe HBTs, remains independent of fluence up to an extreme level of $1x10^{14}$ p/cm^2.

VI. SUMMARY

The proton tolerance of 4^{th}-generation SiGe HBTs is assessed using the observed response of *ac* and *dc* parameters. The results indicate that as SiGe HBTs are scaled to achieve unprecedented levels of performance, their characteristics remain remarkably tolerant to ionizing radiation at even multi-Mrad levels.

VII. ACKNOWLEDGEMENT

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